

Advances in Solid State Joining of High Temperature Alloys

R. Jeff Ding

*Welding Group, NASA-Marshall Space Flight Center
Huntsville, AL, USA*

Judy Schneider

*Mechanical Engineering Department, Mississippi State University
Mississippi State, MS, USA*

Bryant Walker

*Keystone Synergistic Enterprises, Inc.
Palm City, FL, USA*

ABSTRACT

Many of the metals used in the oil and gas industry are difficult to fusion weld including titanium and its alloys. Thus solid state joining processes, such as friction stir welding (FSWing) and a patented modification termed thermal stir welding (TSWing), are being pursued as alternatives to produce robust structures more amenable to high pressure applications. Unlike the FSWing process where the tool is used to heat the workpiece, TSWing utilizes an induction coil to preheat the material prior to stirring thus minimizing the burden on the weld tool and thereby extending its life. This study reports on the initial results of using a hybrid (H)-TSW process to join commercially pure, 1.3cm thick panels of titanium (CP Ti) Grade 2.

KEYWORDS: solid state joining processes; CP-Ti.

INTRODUCTION

While various welding approaches have been applied to high melting temperature materials, joining of CP Ti remains problematic. Various approaches reported include: GTAW, GMAW, laser and more recently hybrid versions of these various processes (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010). The allotropic phase transformation at approximately 980 deg C, often results in a non-homogenous microstructure that varies as a function of the cooling rate (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010). In addition, maintaining adequate inert shielding gases to control the oxidation of the molten pool during fusion welding is difficult (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010).

As an alternative, solid state joining of CP-Ti has also been researched with several studies reported on FSWing of CP-Ti with a variety of tool materials (Lee, et al., 2005, Zhang, et al., 2008).

However in these studies, the main focus was the final microstructure in the stir zone (SZ) and ability to avoid the β -transus during the processing. Thus the ability to precisely control temperature is desirable in joining of CP-Ti to ensure the α -phase is retained during the entire joining process to produce a homogenous microstructure. Lower temperatures in solid state joining are also beneficial as they minimizing oxidation and distortion.

Figure 1 compares the FSW process to the H-FSW process. Similar tooling is used in both solid state joining processes in which some type of probe extends through the thickness of the metal which rotates along with a shoulder to contain the plasticized material. In a FSW, the frictional and deformational heating from the tool shoulder and pin rotation combine to heat the workpiece to a plasticized state. In contrast, the TSW and H-FSW processes use an induction coil to preheat the workpiece to the desired temperature before the weld tool plunges into the weld panel for subsequent stirring. The heating supplied from the induction coil is set slightly below the welding temperature to allow for the deformational heating to raise the material to the desired temperature. Rather than a solid backing plate for the metal to react against, the H-FSW process uses a floating backing anvil or containment plate. As the tool is driven along the length of the weld, the backing anvil tracks the movement of the tool. However, since there is no connection between the tool and the backing anvil, it is referred to as "floating". Metallography of the FSWs weld zone share common features containing a centralized stir zone (SZ) with equiaxed grains separated from the parent material (PM) by a heat affected zone (HAZ).

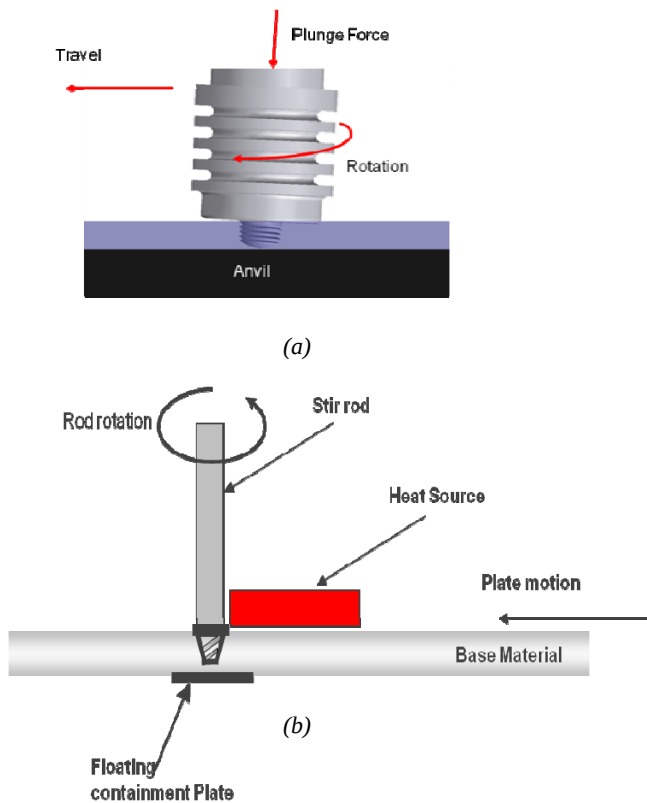


Figure 1. Comparison of the FSW (a) with the H-FSW (b) process used in this study.

EXPERIMENTAL PROCEDURE

A 1.3cm thick plate of CP Ti Grade 2 was received and cut into two each 10cm wide x 220cm long panels. The panels were installed into the solid state joining equipment at the NASA-Marshall Space Flight Center. This equipment is versatile and readily adapts to various solid state joining technologies including FSW, TSW, and H-TSW. The stepped spiral tool geometry shown in Figure 2 was made from 25%Re-W with 4% HfC.

The initial H-FSWs were made in force control over the range of 325-250 RPM, at a travel velocity of 102 mm·min⁻¹, and 22kN plunge force. Weld parameters were based on previous welds in Ti 6/4 (Querín, et al., 2008, Rubisoff, et al, 2009a, b) and were not optimized for the CP-Ti in this study. The induction coil was set to preheat the material to 595° C with an enclosure to provide high purity argon shielding. Independent cooling of the spindle was used to maintain a constant heat profile for the length of the weld. Figure 3 shows the completed H-FSW.

After the H-FSW was completed, the panels were sectioned for metallographic characterization and machined into testing specimens as illustrated in the cut plan in Figure 4. Specimens were machined for tensile testing (20cm long specimens) of the weld in two orientations in addition to compact tension (CT) specimens of two sizes for fracture toughness testing (4.8cm x 4.6cm) and crack growth testing specimens (9.5cm x 9.1cm) also in two orientations with variations in the notch placement.

Tensile tests were conducted in accordance with ASTM Standard E8 (2004) in displacement control at a rate of 1.3mm·min⁻¹. The load frame was equipped with a calibrated 450kN load cell and strain was measured using a 5cm gage length extensometer. Strain measurements were verified post test using pre-test 2.5cm and 5cm

punch marks. Tensile tests were obtained for the PM in the RD (6 each), perpendicular to the weld – LT orientation (9 each), and parallel or along the weld RD - TL orientation (2 each).



Figure 2. The solid state joining equipment at NASA-Marshall Space Flight Center readily adapts to all variations of solid state joining process (a). Tooling configuration used in the H-TSWing of a 201cm panel of CP-Ti (b).

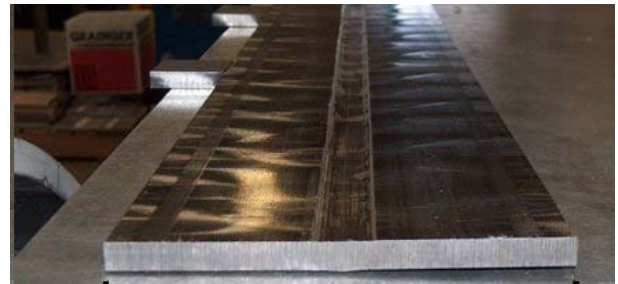


Figure 3. H-FSWed panel of 1.3cm thick CP-Ti.

Precracking and subsequent fracture toughness tests were conducted in accordance with ASTM Standard E1820-09 (2009). Actual dimensions were measured prior to testing on a servo-hydraulic load frame. The load frame was equipped with a 25kN internal load cell and displacement data was obtained from a clip-on displacement gate with a calibrated range of 0.4cm. The specimen was precracked at ambient temperature in load control at approximately 0.6 Kmax. Side grooves were used to ensure crack straightness. The fracture toughness tests were conducted in stroke control with a ramp up rate of 0.13mm·min⁻¹. As illustrated in the cut plan in Figure 4b, the 4.8cm x 4.6cm compact tension (CT) specimens were machined from two orientations LT (perpendicular to the RD) and TL (parallel to the RD). In addition to the two orientations tested, the notch location was varied from the SZ, HAZ, or the PM region.

RESULTS AND DISCUSSION

Results from the mechanical testing of the preliminary CP-Ti H-FSW are summarized in Table I. A slight increase in tensile and yield strength is observed in the H-TSWed specimens with an expected slight decrease in elongation to failure.

Figure 5 shows representative tensile specimens showing similar break location. Note all LT orientation or transverse H-TSW specimens failed to the retreating side (RS) of the SZ, although well outside of the HAZ. The PM was very ductile with an elongation to failure of 42% with only a slight decrease to 30% noted in the H-TSW region.

Fracture toughness measurements are summarized along with the mechanical properties in Table I with a more complete summary in Table II. Table I includes reference values which are listed for comparison (www.matweb.com). Negligible variation was observed

in the K_{IC} fracture toughness as a function of location or orientation. An overall average from all specimens is 59 ± 6 (MPa-m^{0.5}), compared to the published reference value of 66 (MPa-m^{0.5}) (www.matweb.com).

Table I. Mechanical Property Summary

	Ref. Prop.*	PM (TL)	RS SZ (LT)	SZ (TL)
Yield strength (MPa)	344	333 ± 6	353 ± 10	371 ± 4
Ultimate tensile strength (MPa)	275 to 410	449 ± 4	433 ± 6	464 ± 1
Elongation to failure (%)	20	42.0 ± 1.4	27.4 ± 1.9	30.0
K_{IC} (MPa-m ^{0.5})	66	62 ± 1	60 ± 13	57 ± 6

- Range of values listed on www.matweb.com

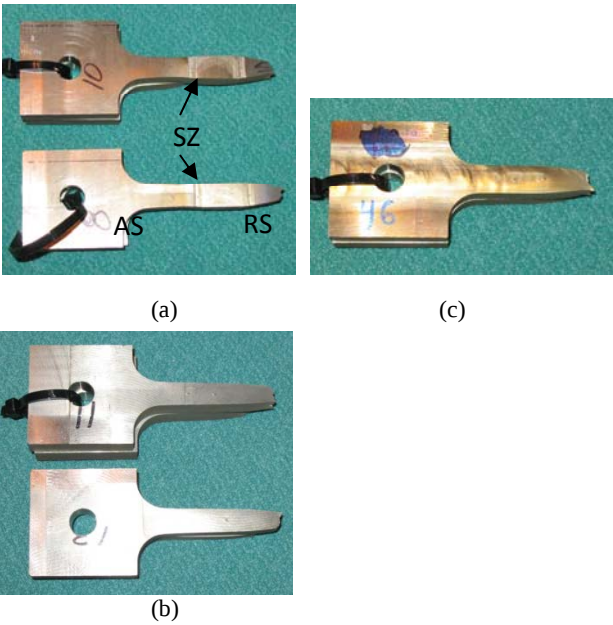


Figure 5. (a) Tensile specimens of PM in TL orientation, (b) of the transverse H-TSW specimens in the LT orientation, and (c) parallel to the weld direction or TL orientation.

The tensile data obtained in this study using non-optimized parameters compares favorably with the reported values in other FSWing processing reports on CP-Ti (Lee, et al., 2005, Zhang, et al., 2008). Although in these studies (Lee, et al., 2005, Zhang, et al., 2008), the length of the weld was not reported nor were details provided on the tool geometry.

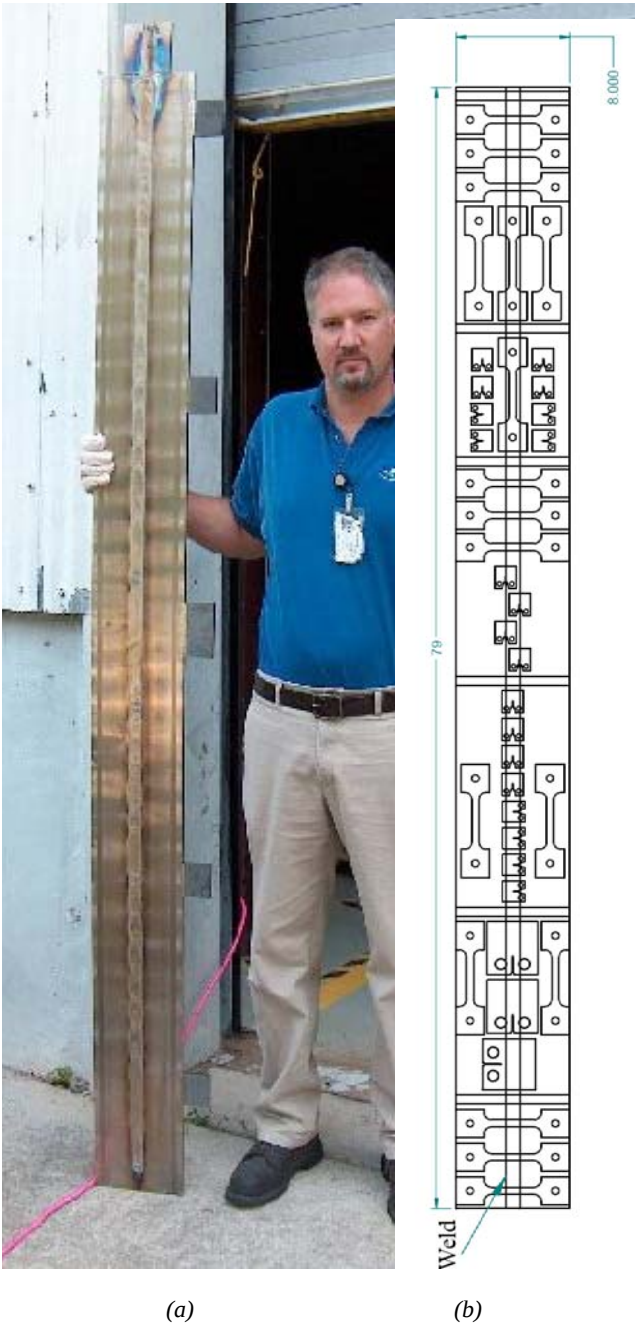


Figure 4. H-TSW operator (203cm tall) shown with the 201cm long H-FSW CP-Ti panel (a) with cut plan (b).

A macrograph of the weld nugget is shown in Figure 6. No defects were observed along the length of the 201cm long weld. Equiaxed grains are observed in the SZ, although detailed microscopy has not been completed. Based on optical metallograph images, minimal HAZ area was observed adjacent to the weld nugget which correlates with the tensile specimens breaking away from the SZ in the PM.

Table II. Negligible variation observed in K_{IC} as a function of orientation.

	Orientation to weld/PM RD	K_{IC} (MPa-m ^{0.5})
PM (T-L)	parallel	62 ± 1
PM (L-T)	perpendicular	60 ± 5
RS SZ (L-T)	perpendicular	60 ± 13
AS SZ (L-T)	perpendicular	63 ± 1
SZ (T-L)	parallel	57 ± 6
SZ (L-T)	perpendicular	53 ± 5



Figure 6. Transverse view of H-TSW nugget taken near the end of the 210cm long weld panel.

SUMMARY

The mechanical property results of the preliminary H-TSW of 1.3cm thick CP-Ti portray a material that possesses high plasticity and good damage tolerance behavior with weld properties very similar to the PM properties in two orientations. After 201cm of H-FSWing, no tool debris was observed in metallographs of the weld nugget or SZ. Further microscopy is needed to determine the overall temperature the material was subjected to during the H-TSWing process. Based on survivability of the tool after 201 cm of weld and lack of tool debris in Figure 6, H-FSWing appears to be a viable method for producing long welds without detrimental tool wear.

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REFERENCES

- ASTM Standard E8, 2004, "Standard Test Methods for Tension Testing of Metallic Materials," ASTM International, West Conshohocken, PA, DOI: 10.1520/E0008-04, www.astm.org.
- ASTM Standard E1820, 2009, "Standard Test Method for Measurement of Fracture Toughness," ASTM International, West Conshohocken, PA, DOI: 10.1520/E1820-09E01, www.astm.org.
- Lathabai, S., Jarvis, B.L., Burton, K.J., "Comparison of keyhole an conventional gas tungsten arc welds in commercially pure titanium," *Mat. Sci. & Engr.*, Vol. A299, p. 81-93, 2001.
- Leary, R.K., Merson, E., Birmingham, K., Harvey, D., Brydson, R., *Mat. Sci. & Engr.*, Vol. A527, p. 7694-7705, 2010.
- Lee, W-B., Lee, C-Y., Chang, W-S., Yeon, Y-M., Jung, S-B., "Microstructural investigation of friction stir welded pure Ti," *Mat. Lett.*, Vol. 59, p. 3315-3318, 2005.
- Li, C., Muneharua, K., Takao, S., Kouji, H., "Fiber last-GMA hybrid welding of commercially pure titanium," *Mat. & Design*, Vol. 30, p. 109-114, 2009.
- Querín, J.A., Rubisoff, H.A., Schneider, J.A., "Effect of weld tool geometry on friction stir welded Ti-6Al-4V," *8th International Conference on Trends in Welding Research Proceedings*, Pine Mt., GA, 2008.
- Rubisoff, H.A., Querín, J.A., Schneider, J.A., "Investigating the effects of pin tool design on friction stir welded Ti-6Al-4V," *FSW&P V*, ed. R.S. Mishra, M.W. Mahoney, T.J. Lienert, pub. TMS, p. 149-157. 2009.
- Rubisoff, H.A., "Microstructural Characterization of Friction Stir Welded Ti-6Al-4V," *MS thesis in College of Engineering*, Mississippi State University, August 2009.
- MatWeb, www.matweb.com, Grade 2 Titanium properties, accessed 1/15/2011.
- Zhang, Y., Sato, Y.s., Kokawa, H., Park, S-H. C., "Stir zone microstructure of commercially pure titanium friction stir welded using PCBN tool," *Mat. Sci. & Engr.*, Vol. 488, p. 25-30, 2008